X-RAY OBSERVATIONS OF STELLAR FLARES

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ABSTRACT

The history of stellar X-ray flare observations prior to EINSTEIN is reviewed. X-ray light curves as measured by the IPC are then presented for all time resolved flare events discovered as of July 1982 in the EINSTEIN data set. These light curves are analyzed in terms of solar-like loop models to derive densities, temperatures, loop lengths, magnetic field strength lower limits, etc. The failure of the model to adequately represent the observations in the case of the YZ CMi flares is discussed. The relationship of X-ray to optical emission and X-ray to UV emission is considered from both an observational and a theoretical viewpoint. It is concluded that the characterization of a flare by a single, time averaged ratio, L_x/L_{opt}, is not physically significant.

I. HISTORY OF X-RAY FLARE OBSERVATIONS BEFORE EINSTEIN

A. Astronomical Netherlands Satellite (ANS)

The first stellar X-ray flare ever observed was the 19 October 1974 event on YZ CMi (Gl 285; dM4.5e; d=5.99 pc) seen by the low energy (0.2-0.28 keV) and medium energy (1-7 keV) detectors onboard the Dutch ANS satellite as reported by Heise et al. (1975). Figure 1 shows the weighted and summed low (LED) plus medium (MED) energy count rates converted to a luminosity, L_x. The background was extremely high and the sensitivity quite low by present standards, as can be seen by the high and fluctuating background in comparison to the quiescent coronal emission (~ 3 x 10^{28} ergs/s) measured by EINSTEIN in 1979, discussed below. The short duration of the event (~ 2 min.) is not too surprising since it must represent only the very peak of a quite energetic flare, L_x(LED+MED) ~ 4 x 10^{30} ergs/s, in comparison to the 1979 EINSTEIN flare, L_x(IPC) ~ 10^{29} ergs/s.

During the first 48 s of the flare, the ratio L_x(MED)/L_x(LED) was about 25, implying a temperature, T ~ 10^7-10^8 K, although this is only

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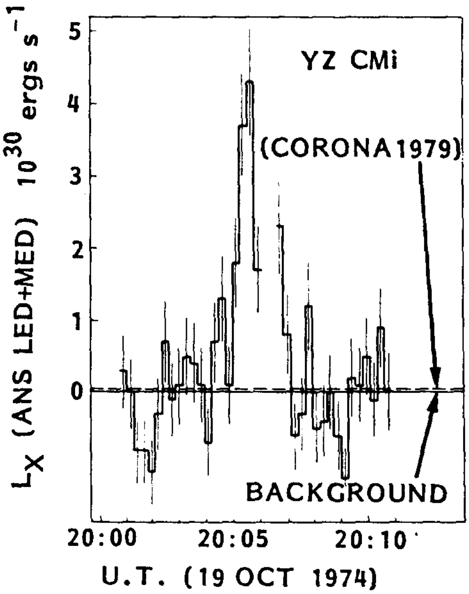

Figure 1. ANS Flare on YZ CMi.

suggestive. Making a crude allowance for radiation outside of the combined passbands, the peak luminosity was $L_x \sim 10^{31}$ ergs/s, and the total energy radiated was $E_x \sim 5 \times 10^{32}$ ergs. No optical data were available for this event.

A second flare observed by the ANS was the 8 January 1975 event on the flare star pair L726-8 + UV Ceti (Gl 65AB; dM5.5e + dM6e; d=2.62 pc; a=2".06), seen by the LED only. The peak luminosity was L_x(0.2-0.28 keV) $\sim 10^{29}$ ergs/s; but if $T \geq 10^7$ K, the total X-ray luminosity would be $L_x \sim 4 \times 10^{30}$ ergs/s (these X-ray "bolometric corrections" are based on emission models of Mewe and Gronenschild (1981), Rosner et al. (1978), and Raymond et al. (1976) among others).

For this event there were simultaneous U and V band observations, from which Haisch et al. (1977) conclude that $L_{opt} \sim$ 5-6 $\times 10^{31}$ ergs/s; we therefore estimate that $L_x/L_{opt} \sim 0.1$.

B. Apollo-Soyuz EUV Telescope

Proxima Centauri (Gl 551; dM5e; d=1.31 pc), a very distant member of the Alpha Cen system (sep. $\sim 2^{\circ}.2$!), was detected during a brief scan by the Apollo-Soyuz EUV telescope in the Parylene filter (44 - 190 A) passband as reported by Haisch et al. (1977); no optical observations were carried out at that time. In retrospect this paper is more important for its discussion and clarification of the "X-ray to Optical Luminosity Ratio" issue than for the EUV data, which have been superceded by the 1979 and 1980 flares observed by EINSTEIN, discussed below, motivated by this early apparent detection.

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C. MIT Satellite SAS-3

YZ CMi was the object of a coordinated X-ray, optical and radio observing program from 30 November - 3 December 1975 using SAS-3 (Karpen et al. 1977). Numerous optical and radio flares were recorded, but no X-ray flares were detected. The brightest optical flare during a time of X-ray monitoring had an estimated luminosity, $L_{opt} \sim 10^{31}$ ergs/s (but note that this is based on an assumed optical emission model by Kunkel as discussed in Haisch et al. 1977). The upper limit $L_x(0.15-0.8$ keV$) < 10^{29}$ ergs/s corresponds at $T \geq 10^7$ K to an upper limit on the total luminosity, $L_x < 2 \times 10^{29}$ ergs/s; we therefore estimate that $L_x/L_{opt} \leq 0.05$.

Prox Cen was the target of a second coordinated X-ray, optical and radio observing program from 16-18 May 1977 (Haisch et al. 1978). The brightest U-band flare yielded $L_{opt} \sim 10^{30}$ ergs/s, again based on Kunkel's emission model. The upper limit on the total X-ray luminosity, assuming $T \geq 10^7$ K, $L_x < 10^{29}$ ergs/s, results in the estimate, $L_x/L_{opt} \leq 0.1$.

D. HEAO-1

The flare star pair AT Mic (Gl 799AB; dM4.5e + dM4.5e; d=8.2 pc) was scanned by HEAO-1 for six days late in 1977. An increase (>9σ) in the LED (0.15-2.5 keV) count rate and an increase (>5σ) in the MED (2-18 keV) count rate occurred on 25 October 1977 (Kahn et al. 1979). A spectral fit resulted in a temperature, $T \sim 4 \times 10^7$ K, a luminosity, $L_x \sim 1.6 \times 10^{31}$ erg/s, and a lower limit for the total flare energy, $E_x > 5 \times 10^{32}$ ergs.

Two suspected flare events on AD Leo (Gl 388; dM3.5e; d=4.85 pc) were inferred by Kahn et al. from a shifting of the centroid of emission away from an unidentified source near that star, and toward AD Leo; this occurred twice on 22 November 1977. Luminosities were estimated to be $L_x \sim 1.5 \times 10^{30}$ ergs/s for both events; however these flare "detections" must be regarded as suggestive only.

II. THE EINSTEIN OBSERVATIONS OF FLARE STARS

In the two and one half years of EINSTEIN operation (November 1978 - April 1981), 40 of the 70 nearby flare stars in the lists of Pettersen (1976) and Kunkel (1975) were targeted for observation by various X-ray instruments, but primarily by the IPC (in fact 57 of the 67 flare star observations utilized the IPC). Despite this substantial number of observations only four significant X-ray flares and five low level minor events have so far (July 1982) been discovered in the data among the nearby flare stars; in addition one major flare was witnessed in the Pleiades (dK?), one in the Hyades involving a (G0 V? + K0 V?) binary, as well as three minor enhancements on other Hyades stars, only

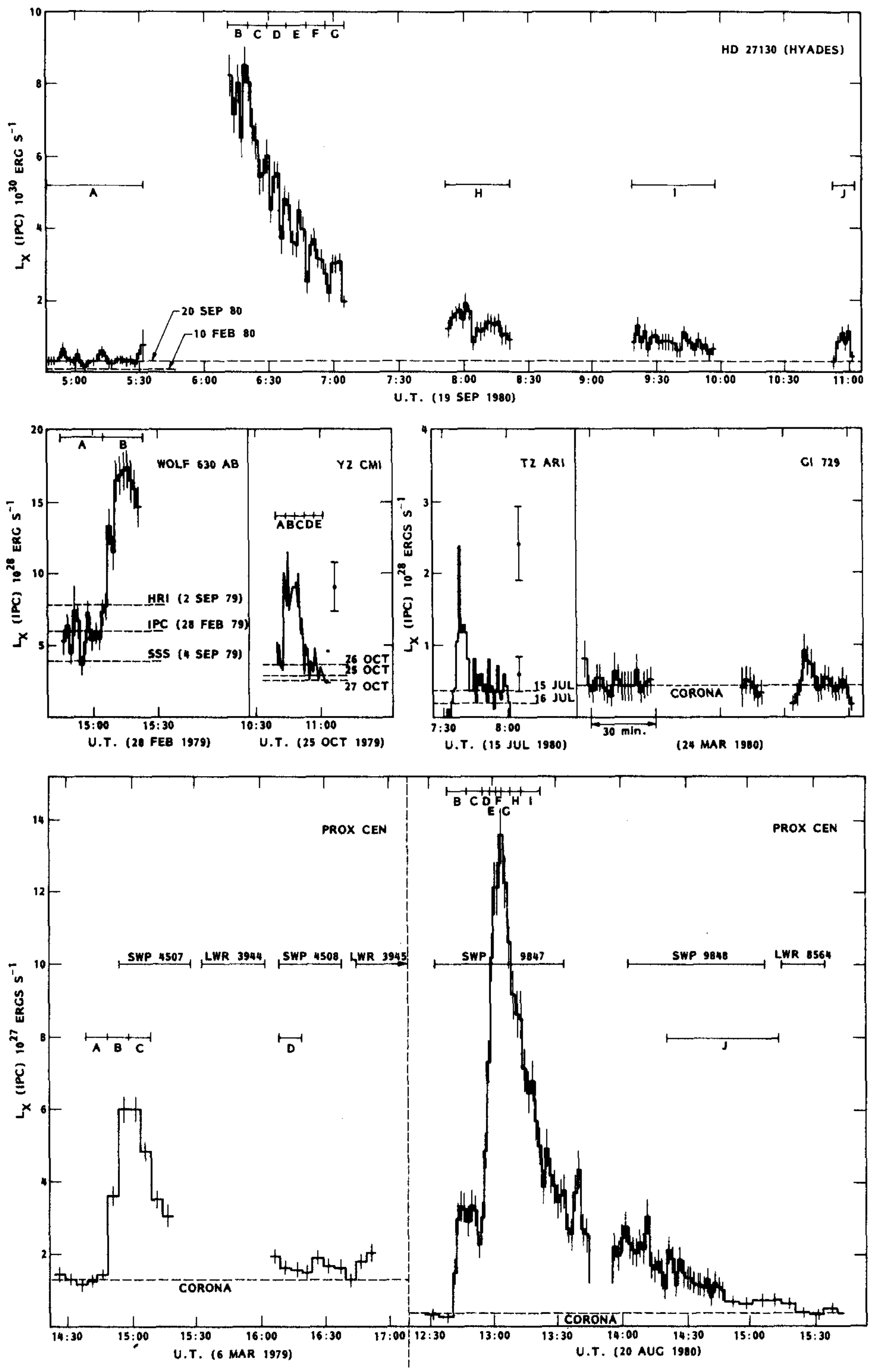

Figure 2. Flare events observed with EINSTEIN

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one of which involved a known flare star. These data are summarized in Table 1.

Not all of the EINSTEIN observations targeted on flare stars have yet been thoroughly scrutinized to identify flare events using various timing analysis procedures; nor have serendipitous observations of flare stars lying in the IPC fields of other targets all been identified and analyzed. Furthermore, the ongoing re-processing of IPC data should increase somewhat the effective lengths of many of the observations.

X-ray IPC light curves are shown in Figure 2 for all noteworthy flare events observed by EINSTEIN. Since all of the stars are at known distances, the X-ray luminosities, L_x (IPC), are presented in this figure. Note the change in scale by a factor of 1000 between the Hyades flare and the Prox Cen flares; the time scale, however, is the same for all the light curves. Various quiescent coronal luminosities are also indicated on these plots, and it is clear that there is secular variation in the quiescent coronae, as one would expect from the behaviour of the solar corona.

Table 1. SUMMARY OF X-RAY FLARES OBSERVED BY EINSTEIN

	Star Name		Sp. Type	Obs. Date	Max/Min	Comments	References
I.	Nearby Stars						
	Wolf 630AB[a]	Gl 644AB	dM3e + dM4e	28 Feb 79	3	Rise, Peak only	Johnson 1981
	Prox Cen[b]	Gl 551	dM5e	6 Mar 79	4	Rise, Peak, part of Decay	Haisch et al. 1980, 1981
	WX UMa[c]	Gl 412B	dM5.5e + dM2	24 May 79	3	No time resolution	Johnson 1981
	YZ CMi	Gl 285	dM4.5e	25 Oct 79	3	Compl. flare; Rel. minor	Kahler et al. 1982
	TZ Ari	Gl 83.1	dM5e	15 Jul 80	4	Compl. flare; Rel. minor	Johnson, these proc.
	Prox Cen[b]	Gl 551	dM5e	20 Aug 80	34	Compl. flare; Rel. major	Haisch et al. 1983
	V1216 Sgr	Gl 729	dM4.5e	24 Mar 81	2	Minimal time resolution	Agrawal et al. 1983
	EQ Peg	Gl 896AB	dM4e + dM5e		<2	Very weak	Golub 1982
	HD 24196		dK5 + dM3		<2	Very weak	Golub 1982
II.	Hyades Stars						
	HD 27130[d]	+16°577	GOV ? + KOV ?	19 Sep 80	>20	Major Event; Post Peak only	Stern et al. 1981, 1982
	HD 27691AB[e]	+14°690	GOV + ?		2-3	No time resolution	Stern and Zolcinski 1982
	vA 500	VR 17	dK?		2	No time resolution	Stern and Zolcinski 1982
	vA 288[f]	VR 6	dM2-3?		2-3	Weak; Long Decay only	Stern and Zolcinski 1982
III.	Pleiades Star						
	HZ 1136		dK?		10	Peak (?); Part of Decay	Caillault et al. 1982

[a] Component A is V1054 Oph; both stars may flare; sep. = 0.218" = 1.3 AU.

[b] α Cen C; sep. from α Cen AB = 7850" = 10^4 AU; probably a bound member of the α Cen system (cf. Walke 1979).

[c] Component A (dM2) is not known to flare; sep. = 28".

[d] Eclipsing Spectroscopic Binary, p = 5.61 d (cf. McClure 1982); analogous to RS CVn Systems.

[e] Spectroscopic Binary, p = 4 d.

[f] Flare Star.

III. ANALYSIS OF FLARE X-RAY LIGHT CURVES: LOOP MODELS

The behaviour of the thermal soft X-ray plasma during solar flares has been outlined by the Moore et al. (1980) summary of the SKYLAB data. And although SMM studies are presently underway which will revise some of our current concepts, the following flare properties are now widely accepted: (1) soft X-ray emission originates from a flare loop or cluster of loops having maximum temperatures of 10-30 x 10^6 K, with T peaking early in the event just prior to the peak of the X-ray emission, and remaining above 10^7 K well into the decay phase; (2) the lengths of the loops, L, range from a few times 10^8 cm for compact flares, to a few times 10^9 cm for subflares, to 10^{10} cm or more for the largest flares; (3) densities at flare maximum are roughly inversely proportional to loop length, ranging from 10^{11}-10^{12} cm^{-3} in compact flares to 10^{10}-10^{11} in large flares; (4) emission measures, EM, range from less than 10^{48} cm^{-3} to greater that 10^{50} cm^{-3} for the largest flares; (5) peak soft X-ray luminosities lie in the range 10^{26} to more than 10^{28} ergs/s; and (6), coronal magnetic fields above active regions, where flares generally occur, are of order, B ~ 100 G.

A. Flare Peak and Initial Decay Phase Analysis

As discussed by Moore et al., near flare maximum there are theoretical as well as observational reasons for believing that the observed 1/e decay time, τ_d, the radiative cooling time, τ_R, and the conductive cooling time, τ_C, are all about equal,

$$\tau_d = \tau_R = \tau_C = 2N_e(\tfrac{3}{2}kT)/N_e^2P(T) = 2N_e(\tfrac{3}{2}kT)/(10^{-6}T^{7/2}/L^2). \qquad (1)$$

This equality of the time scales near flare maximum results in two relations among the four variables, τ_d, T, N_e and L (the loop length) as derived by Stern et al. (1982), if one assumes a known temperature dependence for P(T); we take P(T) ~ $10^{-26.2}$ $T^{½}$. If in addition we assume that the loops giving rise to the X-ray emission are of constant cross section with area, A = $(L/10)^2$, then the loop volume is V = $L^3/100$. We thus arrive at the following relations among τ_d, T, N_e, L and the emission measure, $N_e^2V = N_e^2L^3/100$,

$$T = (4 \times 10^{-5})(N_e^2V)^{1/4}\tau_d^{-1/4} , \qquad (2a)$$

$$N_e = 10^9 (N_e^2V)^{1/8}\tau_d^{-9/8} , \qquad (2b)$$

$$L = (5 \times 10^{-6})(N_e^2V)^{1/4}\tau_d^{3/4} . \qquad (2c)$$

We now apply these relations to the seven EINSTEIN flare light curves shown in Figure 2 and the ANS light curve in Figure 1. Temperatures have been determined from spectral fitting at selected intervals (A, B, C, etc.) for some of the data as indicated on the figure and discussed in the original references; the ANS derived temperature was discussed in § I. Since all temperatures are in the range 10^7–10^8 K, about 50-80% of the total soft X-ray flux will fall within the IPC passband (cf. Table 3 in Haisch and Simon 1982). L^{tot}_{max} is a best estimate of the total X-ray luminosity from which the emission measure may be derived. From eqns. (2) we then calculate T, N_e and L as tabulated for each flare in Table 2.

The flares seem to fall roughly into three groups as shown in Table 2, with the Wolf 630 flare falling somewhat between the properties of groups one and two as discussed below.

In the first group we note the following properties: (1) the calculated and observed temperatures are in fair agreement and are solar-like; (2) the inferred loop lengths are comparable to solar subflares, and are a fraction of the stellar radius, however the corresponding densities are as high as those found in solar compact flares; (3) EM and L_x are comparable to the largest solar flares; and (4), the decay times are shorter than on the Sun, τ_d(Sun) ~ 1000-4000 s.

Overall, these flares seem to be quite similar to moderate sized flares on the Sun except that the densities seem to be an order of magnitude or so higher, which one might expect in the high gravity envi-

Table 2. RISE AND DECAY TIME LOOP MODEL ANALYSIS

	τ_d (s)	L^{tot}_{max} (ergs/s)	T^{obs}_{max} (10^6K)	EM[a]	T^{calc} (10^6K)	N_e (cm^{-3})	L (cm)	R_*[b] (cm)	τ_r (s)	P (d/cm^2)	B (G)	τ_{Alf} (s)
Prox Cen #1	1000	7(27)	17	3.5(50)	30	8(11)	4(9)	1.0(10)	300	6.6(3)	>400	<400
Prox Cen #2	1000	2(28)	27	1(51)	40	9(11)	5(9)	1.0(10)	300	9.8(3)	>500	<450
Gl 729	300	7(27)	--	3.5(50)	40	3(12)	2(9)	1.5(10)	100	3.5(4)	>900	<150
TZ Ari	200	3(28)	--	1.5(51)	65	6(12)	2(9)	1.3(10)	100	1.0(5)	>1600	<100
Wolf 630	(600)[c]	1.5(29)	(30)[d]	7.5(51)	75	2(12)	6(9)	3.1(10)	250	4.2(4)	>1000	<350
YZ CMi #2	120	1.2(29)	20	6(51)	100	1(13)	2(9)	2.6(10)	40	3.5(5)	>3000	<100
YZ CMi #1	80	1(31)	10-100	5(53)	350	3(13)	4(9)	2.6(10)	20	3.2(6)	>9000	<100
HD 27130	3400	>1(31)	30-100	>5(53)	>140	>5(11)	>6(10)	6-7(10)	---	>1.9(4)	>700	<2750

[a]Assuming P(T) ∿ 2 x 10^{-23} erg cm^3 s^{-1}.

[b]Data from Pettersen (1980).

[c]Extrapolation from post-peak turnover.

[d]Not a true thermal spectrum fit.

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ronment of dM stars, and as a result of the high densities EM and L_x are scaled up from the Sun. The decay phase is thus probably controlled by radiative cooling and would thus be shorter than for the same size flare on the Sun by virtue of the higher density.

The two YZ CMi flares constituting the second group are rather different. The observed and calculated temperatures are not at all in agreement, which probably invalidates any resulting estimate of N_e and L; however the extremely short observed decay times do argue in favor of strong radiative cooling and hence high densities as the analysis suggests; EM and L are higher than on the Sun. The Wolf 630 flare also has a discrepancy in the temperatures, although not as great as in the case of YZ CMi (but note also that the temperature derived by spectral fitting of the IPC data is not based on a true thermal spectrum as discussed by Johnson in these proceedings). The Wolf 630 and YZ CMi #2 flare are quite similar in EM and L, but the Wolf 630 N_e is lower although this depends on the poorly known decay time of the Wolf 630 event. By and large the Wolf 630 flare seems to lie somewhere between the first and second group; overall the YZ CMi flares suggest much denser and perhaps more energetic phenomena than are seen on the Sun based on this analysis. In § V however, we present arguments that indicate that this type of analysis is not particularly appropriate for the case of YZ CMi.

Lastly, the Hyades flare (HD 27130), the most energetic of the events, appears to represent a very large scale event with $L \sim R_*$ and a long cooling time suggesting moderate, solar-like density.

B. Flare Rise and Magnetic Field Strength Analysis

The currents giving rise to coronal magnetic structure are primarily deep in the atmosphere and below, with only a small fraction of the field arising from currents in the corona itself; it is the annihilation of these coronal currents which is thought to energize the flare plasma. Thus the magnetic pressure at the time of the flare will still be greater than the gas pressure,

$$\frac{B^2}{8\pi} > P \; . \qquad (3)$$

We therefore use the results of the previous analysis to calculate lower limits on B, as presented in Table 2. These values are intrinsically of interest because they suggest considerably stronger magnetic fields than on the Sun, especially for YZ CMi, although of course in the case of those events the previous analysis is questionable in the first place.

In addition, the magnetic field strengths also provide a crude theoretical constraint on the flare rise time, τ_r. The lower limits on B give us a lower limit on the Alfven velocity,

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$$v_A = B/(4\pi\rho)^{1/2} \quad . \qquad (4)$$

The limit on v_A translates into a constraint on the theoretical flare rise time, τ_A,

$$\tau_A = L/\varepsilon v_A \quad , \qquad (5)$$

where εv_A is the propagation velocity for the magnetic instability. There are theoretical reasons for believing that $\varepsilon \lesssim 0.1$ (Antiochos, priv. comm.) and since we have only a lower limit on v_A we take $\varepsilon = 0.1$ to derive τ_A as tabulated in Table 2. Although there are too many uncertainties to place much credence in agreement between the upper limits on τ_A and the observed τ_r in any individual case, the general trend seems to be in the right direction and is encouraging. It is of course unfortunate that τ_r is unknown for HD 27130 since this event would have apparently provided a critical test; all we know is that $\tau_r < 2500$ s.

C. Flare Energy Analysis: The "Continued Heating" Problem

According to Moore et al., in the large two-ribbon solar flares heating of the thermal plasma continues far into the decay phase, as manifested by the continuous creation of new, higher, $T \sim 10^7$ K, loops, presumably by filling up via chromospheric evaporation; the compact flares show less evidence for continuous heating.

We again address the issue of similarity between the solar and stellar flare phenomenon by asking whether there is any evidence for continued heating in these eight flares. From the previous analysis we have estimates of T, N_e and L at flare maximum; the total plasma energy after the primary heating phase is therefore,

$$E = 2N_e(\tfrac{3}{2}kT)\; L^3/100 \quad . \qquad (6)$$

The total amount of energy radiated away, E_r, can be estimated from the light curves with an appropriate "bolometric correction". If $E_r < E$, there is no need to invoke additional heating (although of course a detailed model of the time dependence of the energy balance allowing for conduction and mass motions could still suggest heating even if $E_r < E$, but the present data do not warrant this level of modeling); whereas $E_r > E$ would definitely require additional continued heating. In Table 3 we present best estimates of E and E_r for the eight flares.

We find evidence for continued heating in both of the Prox Cen flares and in the Wolf 630 event; however the Wolf 630 thermal plasma parameters are too uncertain to be very convincing. On the other hand the Prox Cen results, especially for the second (20 Aug) flare, do provide credible evidence for continued heating; the determination of

Table 3. ESTIMATED THERMAL ENERGY AND RADIATED ENERGY

Star	E (ergs)	E_r(ergs)
Prox Cen #1	6(30)	1.2(31)
Prox Cen #2	2(31)	3.5(31)
Gl 729	4(30)	1.5(30)
TZ Ari	1.3(31)	5(30)
Wolf 630	1.3(32)	>1.6(32)
YZ CMi #2	3(31)	3(31)
YZ CMi #1	3(33)	5(32)
HD 27130	>6(34)	>3(34)

E_r for the second flare ($E_r \sim 3.5 \times 10^{31}$ ergs) is based on detailed bolometric corrections possible as a result of the numerous temperature determinations during the flare alluded to in Figure 2 and discussed in Haisch et al. (1983); the loop model analysis leading to the estimate, $E \sim 2 \times 10^{31}$ ergs, is fairly well substantiated by the agreement of the calculated and observed maximum temperatures for that flare.

IV. RELATIONSHIP OF SOFT X-RAY TO OPTICAL EMISSION

The determination of the ratio, L_x/L_{opt} for a given flare as a test of various models has received a great deal of attention in the past several years, especially as a result of the scaling law analysis and the resulting predictions for various flare stars by Mullan (1976). In the above review of observations we have cited several events characterized by $L_x/L_{opt} < 1$; in other papers, ratios $L_x/L_{opt} > 1$ are derived for a given flare (cf. Kahn et al. 1979; Haisch et al. 1981). In fact, as Kahler et al. (1982) clearly and correctly point out, the ratio L_x/L_{opt} varies dramatically throughout the course of a flare event: in the case of their YZ CMi flare, ranging from ~ 0.08 to infinity!

In order to make sense of this it is necessary to again look to the Sun for guidance. The three principal ingredients in a solar flare are: Hα emission, soft X-ray emission and hard X-ray bursts. Unfortunately, there is no universally accepted model regarding the interrelationships of these phenomena, but recent SMM data are providing important new results.

The Hα event itself consists of two distinct phenomena: the rapid, spiky brightenings seen in the Hα kernels and the later appearance of bright, relatively stable Hα loops spanning the magnetic neutral line. As discussed by Zirin et al. (1981) the soft X-ray emission of the thermal phase is closely connected with the formation of the system of Hα loops; whereas the rapid variability seen in Hα kernels (and in the brightenings of transition region lines) is similar to the temporal behaviour of the hard (> 20 keV) X-rays of the impulsive phase (Leibacher, private communication).

As a result of SMM, there is now evidence, from direct chromospheric observations, of chromospheric evaporation driven by two mechanisms: heating by non-thermal, flare accelerated electrons during the impulsive phase; and heating by thermal conduction during the thermal phase (Acton et al. 1982; Antonucci et al. 1982).

We thus arrive at the following general scenario for the phenomenology of a flare. Hard X-ray bursts result from the deceleration of non-thermal electrons as they bombard the dense chromosphere, with the burst size and timing presumably reflecting the magnetic energy release sequence. Chromospheric material is immediately heated and evaporated, and the Hα and transition region line brightenings reflect the rapidly varying heating function. There is a maximum temperature for the heated flare material predicted by dynamic loop models $T_{max} \sim 30 \times 10^6$ K (Pallavicini, private communication); the evaporating material quickly reaches a temperature of this order, but it takes some time for the loops to fill up as conduction and downward irradiation redistribute energy (and there may be additional heating going on as well as discussed in § III), all of which smooth out the temporal behaviour of the soft X-ray emission, which presumably is coming mainly from the tops of the hot loops. Higher and higher loops are filled up; as the lower loops cool, we see loop structure in Hα.

In this context, the spiky nature of the U-band flare reported by Kahler et al. for the 1979 YZ CMi flare is interpreted as a manifestation of the impulsive heating phase, since the U-band brightening can be associated with chromospheric enhancement at temperatures of 7500-9500 K, as shown by the flare spectrophotometry of Mochnaki and Zirin (1980), which we take as evidence of chromospheric heating and evaporation due to fast electron bombardment. The first and peak U-band "burst" coincides exactly with the onset of the soft X-ray, thermal event. In other words, we take the U-band spikes as a proxy indicator of hard X-ray bursts; with this interpretation it is instructive to compare Figure 2 of Kahler et al. (1982) with Figure 1 in Zirin et al. (1981).

We conclude that the characterization of a flare by a single, time averaged ratio, L_x/L_{opt}, is not of any particular significance; instead, observations of the detailed time dependence of various diagnostics within the context of a flare model are required. Cram and Woods (1982) have done preliminary studies of the responses of certain such spectral signatures to various candidate energy transport processes in models of stellar flares.

We note that observation of the hard X-ray, impulsive phases of stellar flares has heretofore been impossible since the sensitivity of even such instruments as the EINSTEIN Monitor Proportional Counter (MPC) has been restricted to energies less than 20 keV. However, the forthcoming EXOSAT mission will be sensitive to 50 keV with a reasonably high collecting area using the Medium Energy Experiment, and to 80 keV with the much smaller effective area Gas Scintillation Proportional Counter (GSPC) experiment. Hard X-ray flare measurements should provide an important new diagnostic for stellar flare models.

V. CRITIQUE OF THE YZ CMI LOOP MODEL RESULTS

In § III a detailed analytical procedure was outlined based on a simple solar model as discussed by Moore et al. (1980) and Stern et al. (1982); the results of this analysis appeared to be self-consistent for some of the flare events, but questionable for others, particularly for the YZ CMi flares. We now assume, as discussed in § IV, that the U-band spikes observed at the onset of the YZ CMi flare are indeed indicative of impulsive heating at the footpoints of loops and are characterized by the chromospheric flare temperatures observed by Mochnaki and Zirin (1980).

In fact, a continuum spectrum was obtained by Kahler et al. (1982) at 10:43 UT coinciding with the first, peak U-band spike which is fairly well fit by a Planck function at $T \sim 8500$ K. The projected area can then be derived from the known surface flux, πB_λ ($T = 8500$ K), and the observed flux at the earth in the U-band; Kahler et al. derive a projected area, $A_\mu \sim 10^{19}$ cm^2. If this emission arises at the footpoints of one or more loops which are in the process of being filled up by chromospheric evaporation, and if the cross section of the loop or loop cluster is $(L/20)^2$ for loops of length L (i.e. diameter one-tenth the length), then we find $L \sim 3.5 \times 10^{10}$ cm. This is in sharp contrast to the loop model analysis result of § III, wherein it was estimated that $L \sim 2 \times 10^9$ cm for this event. This dramatic change in L would of course significantly alter the estimates of N_e, T, B, etc. The moral here is that as attractive as simple loop models and scaling laws such as those outlined in § III might be as analytical tools, they may lead to quite misleading results when general characteristics of flares on the average are applied to individual cases.

VI. RELATIONSHIP OF SOFT X-RAY TO UV EMISSION

As indicated on Figure 2, simultaneous IUE and EINSTEIN observations were carried out during both of the Prox Cen flares (cf. Haisch et al. 1980, 1981, 1983 for details). Only quiescent chromospheric and transition region emission was observed during the 1979 event (Haisch and Linsky 1980); however during the 1980 event an IUE short wavelength, low dispersion flare spectrum was obtained coinciding with the peak of the X-ray flare. The total flare energy in the transition region lines of He II, C II, C IV, N V, Al III and Si IV was 1.2×10^{30} ergs; the total X-ray energy during the time of the IUE exposure was 2.5×10^{31} ergs, or in other words, $E(\text{X-ray})/E(\text{TR}) \sim 20$.

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This single energy ratio averaged over the impulsive phase and most of the thermal phase of the flare suffers from the same deficiencies as does the single, average L_x/L_{opt} ratio discussed in § IV; and unfortunately given the sensitivity of the IUE and the low flux levels of even the brightest transition region lines, detailed time-resolved UV flare spectra will probably have to await the coming of the Space Telescope.

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DISCUSSION

Vaiana: Of course loop modelling should not be applied to flares. One of the basic hypotheses of loop models is hydrostatic equilibrium. It is true that Pallavicini has found that scaling applies to the less-than-impulsive phase of several stellar flares. Ignoring this basic difficulty for a moment, however, and, assuming that there is some way in which scaling can be applied, I wonder whether there is a way round the difficulty in the case of YZ CMi. If I understand this difficulty it is that when you do a total volume analysis you come up with loop lengths which are an order of magnitude greater than those you derive from radiative cooling times for the flare. Given that the quiescent corona of YZ CMi is very different from that of Prox Cen (the temperature is higher giving a higher volume coverage as well as, perhaps, higher pressure) I wonder whether a way round the difficulty, assuming you want to adhere to the loop model, which I do not, would be to have the same kind of intermittency in loops as in the Sun. If one has, for istance, 10 loops emitting at the same time then one has the required area coverage, all of them will be at the high density required by the cooling rate while the total emission will be compatable with your other analysis based on volume factors. That is, instead of having one loop of 10^9cm in length you will have 10 of them all having essentially the plasma parameters that are advocated by time changes.

Haisch: I think I agree with everything you have said but I am not sure that it makes a great deal of difference as to what kind of corona the flare is embedded in. The flare analysis depends only on equating various time-scales i.e. the conductive cooling time, the radiative cooling time and the observed cooling time. So what kind of loops might be present in the atmosphere before, during or after the flare is not relevant.

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Vaiana: But in the one you are analysing you find loop lengths of a few times 10^{10}cm.

Haisch: But that was based on the observation of a certain amount of flux in the U-band and the fitting of the spectrophotometry to a black body at a certain temperature.

Jordan: I think we are getting into too much detail for general discussion.

Haisch: Basically I think we are in agreement (laughter).

Serio: I would like to comment on your suggestion that there might be continuous heat deposition after the maximum of the flare. We have analysed quite a lot of SMM data with the aid of a numerical lodel for flares in loops and found no evidence for heat deposition after the temperature maximum. Your result may be explained if after the maximum there is continuous input of hot matter evaporated from the chromosphere. So the comparison of the radiated energy with the energy content at any time may be misleading.

Haisch: All I am saying is that if I take the integrated energy emitted during the flare, especially for the two Prox Cent events, then, having carefully applied realistic bolometric corrections, I see that 12 x 10^{30} ergs was radiated by the first flare and somewhat more by the second. So these are well determined numbers. But I do not know how much energy was there in the plasma to begin with except in so far as I have estimates from the application of the loop model and so on. If one accepts those loop models then I see that there is twice as much energy being radiated as was stored in the plasma. Furthermore, I know that there are additional losses besides radiation. For istance, half of the radiated energy is radiated downward and there is energy conducted away. So if the energy losses are larger than the energy stored then that would seem to be evidence for continuous heating. On the other hand the estimate of the energy stored is based on a model calculation and it is not clear to what extent one should believe that. There could be a factor of 2 uncertainty or there could be a factor of 10.

Jordan: May I make a comment? By equating the radiated and the conducted energy losses through the cooling time you are, in effect, adopting a condition of minimum energy loss. That method will always underestimate the total energy loss.

Haisch: By how much?

Jordan: I don't know. It depends on what else you may be doing, but it will certainly tend to under rather than overestimate the losses.

Mullan: I have 3 comments. First, the comparison of radiative and conductive cooling in the Sun was done many years ago by Moore and Atlow and they showed that the conductive cooling was much more important right at the flare maximum. Secondly, any assumption of black body emission from a flare seems totally irrelevant. I cannot imagine any circumstances in which the chromospheric emission from a flare would have anything to do with a black body. My third and major point concerns the bolometric corrections. It is well known that the corrections to the optical radiation from a flare is a very difficult problem. As far as I know it is subject to errors at least as large as 200, depending on which model you take for the flare emission. I am therefore not very upset by errors of a factor of 2 in the estimated radiated losses. I also do not believe that values of L_X / L_{opt} evaluated only within certain bands mean anything. You might as well say that I went to the USA last week and did not see you there. So you were not there (laughter). The point is that there is much emission from the chromosphere which has not been seen. (Rest of comment lost).

Haisch: Let me reply to those 3 comments if I can remember them all. The equating of radiative and conductive cooling times at flare maximum I took from Ron Moore's summary of the Skylab data. That was based on both empirical data and theoretical consideration from solar flares. If one pictures a flare as a loop filling up with plasma, this hot plasma arises from conductive flux heating material lower down. Once the radiation begins to exceed conduction as a cooling mechanism then less conduction takes place, leading to a fall-off in the supply of hot plasma and so the light curve turns over. There are theoretical considerations but I believe that there are also Skylab data, which support this balance of conductive and radiative timescales at flare maximum. The second point concerns the use of black body curves. Well this is justified by the observations of Zirin and Mochnacki. They carried out spectrophotometry of flares on YZ CMi and found that the radiation could be fitted to black body distributions at temperatures of 8000-10 000 K. If one has flares characterized by such temperatures I do not see how you can get bolometric corrections ∿ 200. If one is looking in the U and B optical bands then one expects to pick up more than 0.5% of the total radiation. Perhaps if one had, a 10 000 000 K radiation temperature this could be so.

Priest: I think that when you are quoting solar results from Skylab you should be very critical of them. In particular, when people calculate conductive cooling times there are many uncertainties. It is especially true that when dealing with flare plasma it is likely to be highly turbulent and so one should use turbulent conductivity in calculations rather than "classical" turbulence. Another problem is that of knowing what the correct length scale is. You see on the Sun one may see some kind of elongated structure in X-rays. That does not mean that the field lines run along its length. They may indeed be directed across it. So great care is needed.

Haisch: I agree with what you are saying. What is needed is more observations and better analysis of solar flares so that we can develop a more sophisticated approach. All I wanted to do here was to show what could be done using our present knowledge and it is obvious that strange results occur as a result.

Jordan: Having restrained myself thus far I would like to make a comment. If you are using the scaling law which you have used you will probably get the electron temperature about right but the electron pressure will always be overstimated. The scaling law is in fact the condition that the pressure be a maximum for the solution as Tony Hearn has pointed out. You can show that very easily on a curve of temperature against pressure. The scaling laws give the locus of critical solutions. This is similar to the work that Hood and Priest have done on thermal stability. The critical point, which is the peak on the curve, is always the maximum pressure point but the critical temperature is never far from the real temperature. So if you want a good estimate of the temperature but a bad estimate of the pressure then the scaling law approach may be a reasonable one.

Haisch: If one always overestimates the density then that would agree with what I find here.

Jordan: You really do not need to estimate the pressure however. If you have the X-ray luminosity and have measured temperature and know the radius of the star, you can find the mean coronal density or the mean pressure. Since these are high pressure objects the pressure will be roughly constant down to the transition region. You can then work from that point and model the pressure. I would encourage that approach.

Haisch: That's right. In fact the system is overdetermined. There was a temperature predicted and a temperature observed and you can compare those two or you could just as well compare the densities.

Linsky: There are two aspects of the data which you did not mention for lack of time. The first is that the temperature peaks before the soft X-ray luminosity by a few minutes. I think that this has been seen in several flares and is typically seen in solar flares. Secondly, there is some evidence for absorption after flare maximum. Would you like to comment on these apsects.

Haisch: I did not plant Jeff (Linsky) in the audience but I am glad he mentioned these points. During this event as well as during the 1979 event (on Prox Cen?) we found that the peak temperature did in fact preceed the X-ray luminosity by 2-3 minutes. When we carried out the standard Einstein processing on the decay part of the 1980 flare we had two free parameters, viz the temperature and the mass column density in the line of sight. During a short time interval in the decay we found a temporary increase in this column density to a significant number i.e. $10^{20}cm^{-2}$. The mass column density derived for the rest of the flare was negligible. So we attribute this to mass ejection during the flare and draw an analogy with the solar Hα two-ribbon flare.